



Additional Results of Glaze Icing Scaling in SLD Conditions

Jen-Ching Tsao
Ohio Aerospace Institute

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Outline

- Background
 - Progress on scaling method development
- Test Objective
- Test Description
- Ice Shape Comparisons
- Conclusion



Modified Ruff Method

- Current recommended method for size scaling
 - In App-C & SLD



Modified Ruff Method

- Current recommended method for size scaling
 - In App-C & SLD
 - Match modified inertia parameter K_0 for scale MVD_S

$$K_0 = \frac{1}{8} + \frac{\lambda}{\lambda_{Stokes}} \left(K - \frac{1}{8} \right)$$



Modified Ruff Method

- Current recommended method for size scaling
 - In App-C & SLD
 - Match modified inertia parameter K_0 for scale MVD_S
 - Match stagnation-point freezing fraction n_0 , with a scale LWC_S at user's choice, to find scale $t_{tot,S}$

$$n_0 = \frac{C_{p,ws}}{\Lambda_f} \left(\varphi + \frac{\theta_0}{b_0} \right)$$



Modified Ruff Method

- Current recommended method for size scaling
 - In App-C & SLD
 - Match modified inertia parameter for scale MVD_S
 - Match stagnation-point freezing fraction n_0 , with a scale LWC_S at user's choice, to find scale $t_{tot,S}$
 - Match accumulation parameter A_c for scale τ_S

$$A_c = \frac{LWC V \tau}{d \rho_i}$$



Modified Ruff Method

- Current recommended method for size scaling
 - In App-C & SLD
 - Match modified inertia parameter for scale MVD_S
 - Match stagnation-point freezing fraction, with a scale LWC_S at user's choice, to find scale $t_{tot,S}$
 - Match accumulation parameter for A_c for scale τ_S
 - Match Weber Number $We_L (= \rho_w V^2 d / \sigma_{w/a})$ for scale V_S

$$We_L = c, \Rightarrow V_S = V_R \left(\frac{d_R}{d_S} \right)^{1/2}$$



Potential Method for SLD Glaze Icing

- Feo (2007) proposed a slightly different approach
 - Match film Weber Number for scale V_S

$$We_f = \rho_w V_f^2 h_f / \sigma_{w/a}$$
$$We_f = c, \Rightarrow V_S = V_R \left(\frac{d_R}{d_S} \right)^{2/3}$$

- Match SLD film thickness correlation for scale LWC_S

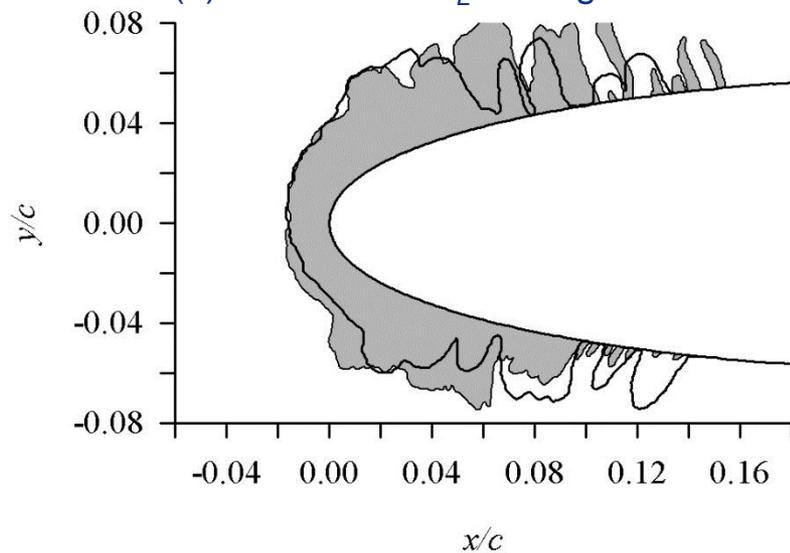
$$\frac{h_f}{d} = c, \Rightarrow LWC_S = LWC_R \left(\frac{d_R}{d_S} \right)^{-0.7}$$



Typical Scaling Results

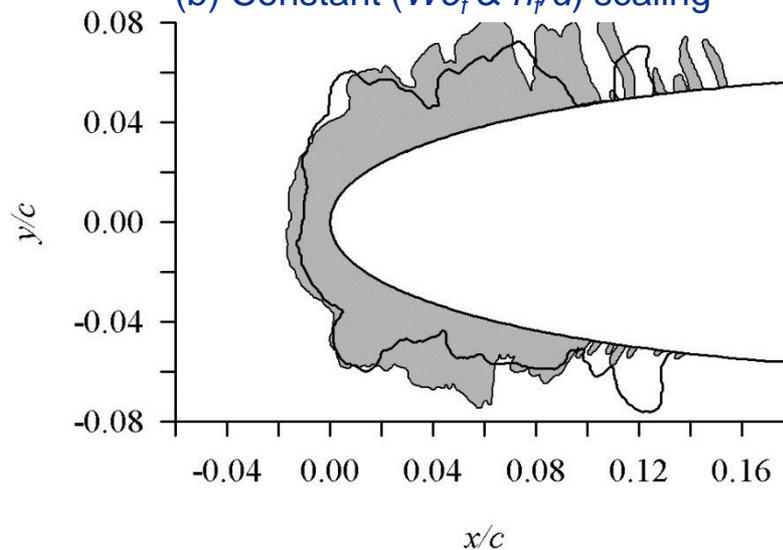
$$V_R = 100 \text{ kt}, MVD_R = 195 \mu\text{m}, n_0 = 0.3$$

(a) Constant We_L scaling.



$c = 91.4 \text{ cm}$, 09-26-08 Run 1
 $c = 35.6 \text{ cm}$, 09-30-08 Run 2

(b) Constant (We_f & h_f/d) scaling



$c = 91.4 \text{ cm}$, 09-26-08 Run 1
 $c = 35.6 \text{ cm}$, 09-30-08 Run 1

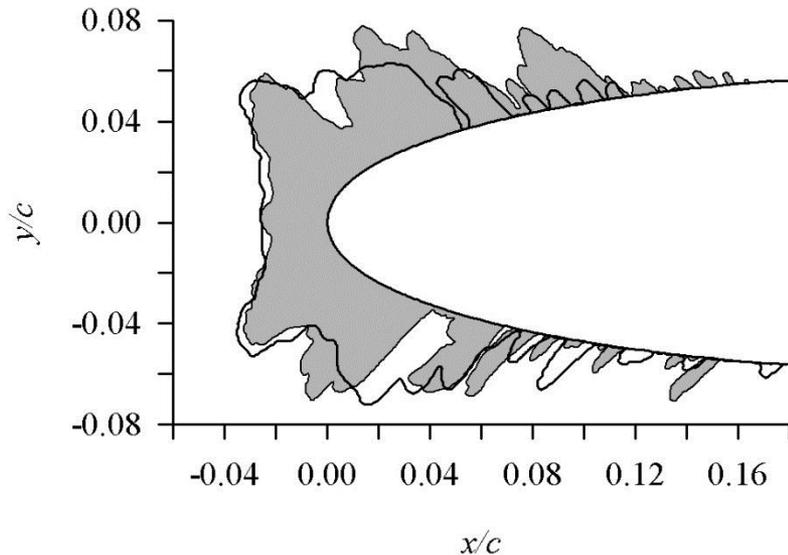
		t_{tot}	V	MVD	LWC	τ	β_0	$\beta_0 A_{c^*}$	n_0	We_L	We_f	h_f/d
		$^{\circ}\text{C}$	kt	μm	g/m^3	min	$\%$			10^6	10^{-16}	10^{-9}
	Ref	-7.8	100	198	1.08	14.0	96.3	1.69	0.31	1.17	0.74	0.82
	(a)	-2.9	159	87	0.57	6.6	96.2	1.73	0.31	1.16	0.86	1.04
	(b)	-2.7	185	86	0.54	5.7	96.4	1.63	0.32	1.56	0.72	0.84



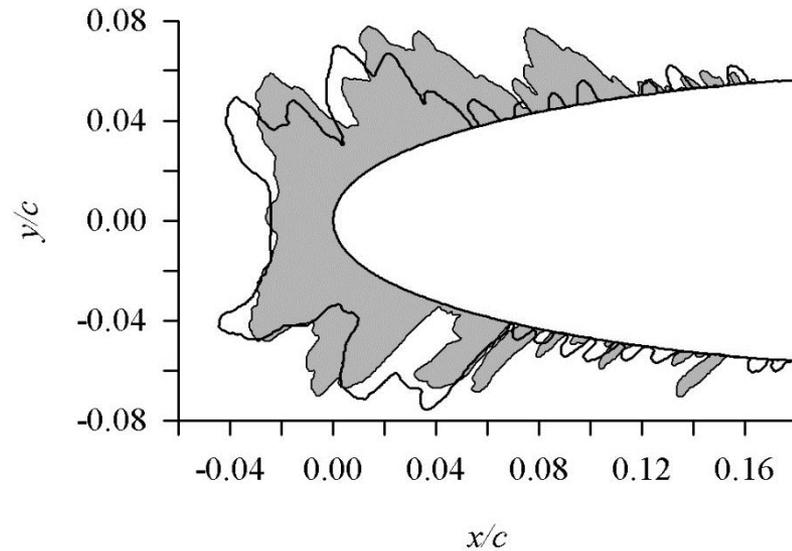
Typical Scaling Results

$$V_R=100kt, MVD_R=195\mu m, n_0=0.5$$

(a) Constant We_L scaling.



(b) Constant (We_f & h_f/d) scaling



— $c = 91.4$ cm, 09-26-08 Run 3

— $c = 35.6$ cm, 09-30-08 Run 5

— $c = 91.4$ cm, 09-26-08 Run 3

— $c = 35.6$ cm, 09-30-08 Run 6

	t_{tot}	V	MVD	LWC	τ	β_0	$\beta_0 A_{c^*}$	n_0	We_L	We_f	h_f/d
	$^{\circ}C$	kt	μm	g/m^3	min	%			10^6	10^{-16}	10^{-9}
— Ref	-14.1	100	198	1.07	14.0	96.3	1.69	0.52	1.18	0.74	0.81
— (a)	-5.9	159	87	0.57	6.6	96.2	1.73	0.51	1.16	0.87	1.03
— (b)	-6.0	186	86	0.54	5.7	96.4	1.64	0.53	1.58	0.72	0.83



Test Objective

- Data for larger model size and size ratio
- Expanded SLD conditions in IRT
- Strong glaze icing regime



Test Description

- NASA Glenn Icing Research Tunnel (IRT)
- 72-in and 21-in-Chord NACA 0012 (size ratio 3.4:1)
- $AOA = 0^\circ$
- $n_0 = 0.2, 0.3$
- Reference MVD's – 85 μm and 170 μm
- Reference Velocities – 100 kt and 130 kt

NACA 0012 Test Models in IRT



reference model (72")



scale model (21")

Ice Shape Photographs

(a) reference



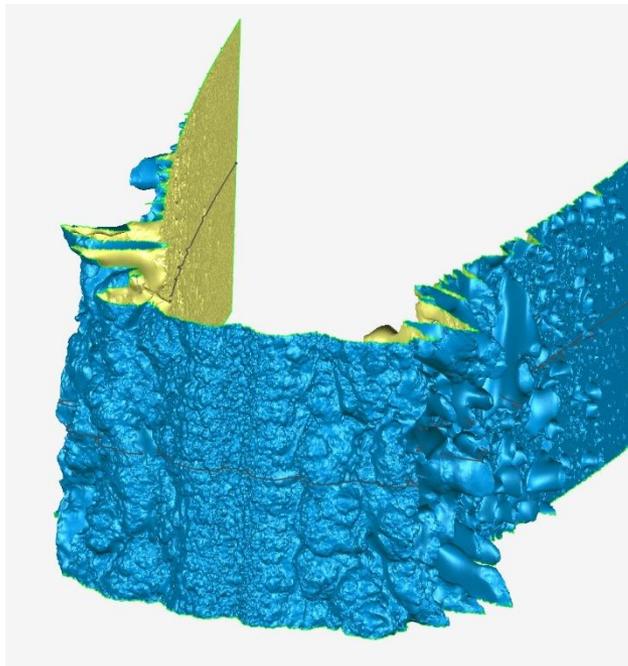
(b) scale



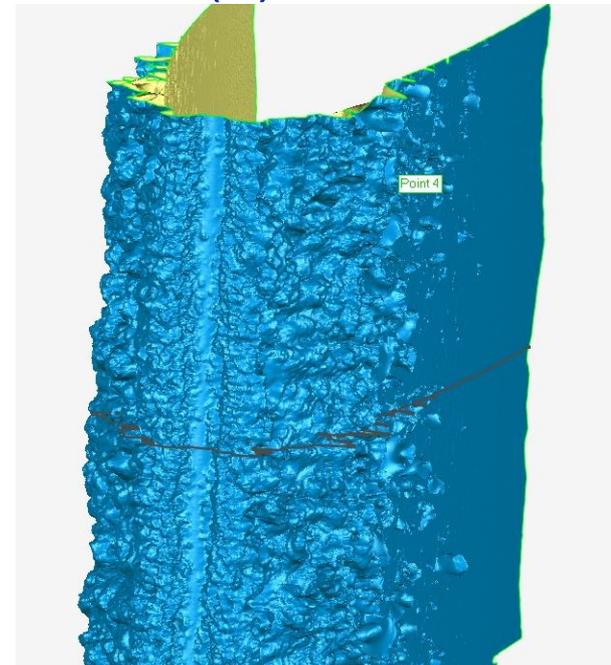
Date/Run	c in	t_{tot} $^{\circ}C$	V kt	MVD μm	LWC g/m^3	t min	b_0 %	A_c	$b_0 A_c$	n_0	We_L 10^6
(a) 12-1-14/3	72	-6.0	99	84	1.2	23.2	82.9	1.61	1.33	0.20	2.30
(b) 1-19-16/6	21	-2.7	184	31	1.0	4.4	83.2	1.62	1.35	0.21	2.33

3-D Scanned Ice Shapes

(a) reference



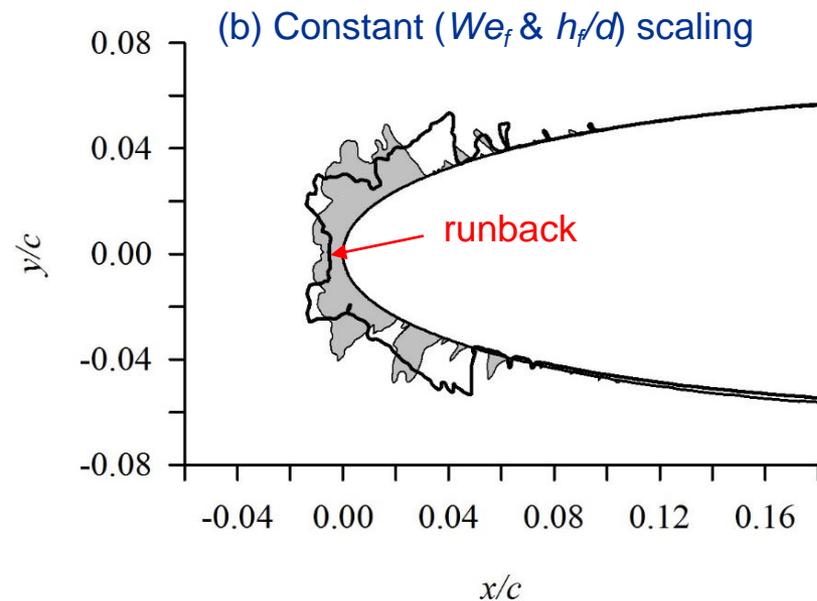
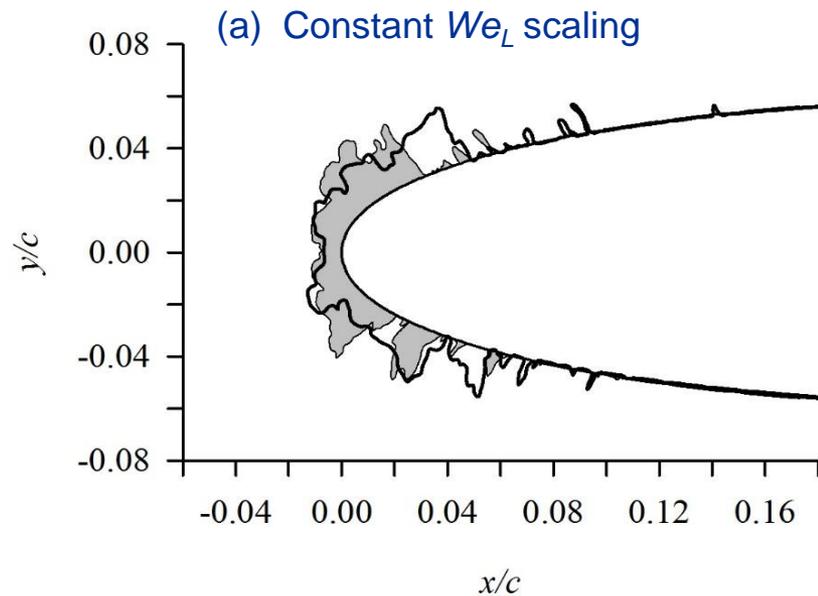
(b) scale



Date/Run	c in	t_{tot} °C	V kt	MVD μm	LWC g/m^3	t min	b_0 %	A_c	$b_0 A_c$	n_0	We_L 10^6
(a) 12-1-14/3	72	-6.0	99	84	1.2	23.2	82.9	1.61	1.33	0.20	2.30
(b) 1-19-16/6	21	-2.7	184	31	1.0	4.4	83.2	1.62	1.35	0.21	2.33

Ice Shapes Comparison (1)

$$V_R=100\text{kt}, MVD_R=85\mu\text{m}, n_0=0.2$$



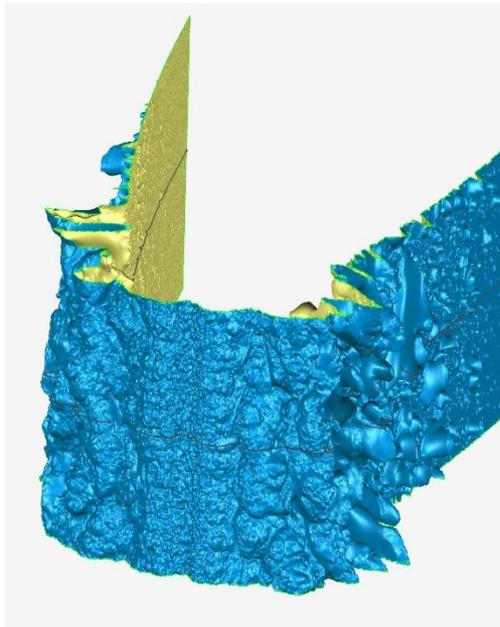
 $c = 72$ in, 12-01-14/03
 $c = 21$ in, 01-19-16/06

 $c = 72$ in, 12-01-14/03
 $c = 21$ in, 01-19-16/01

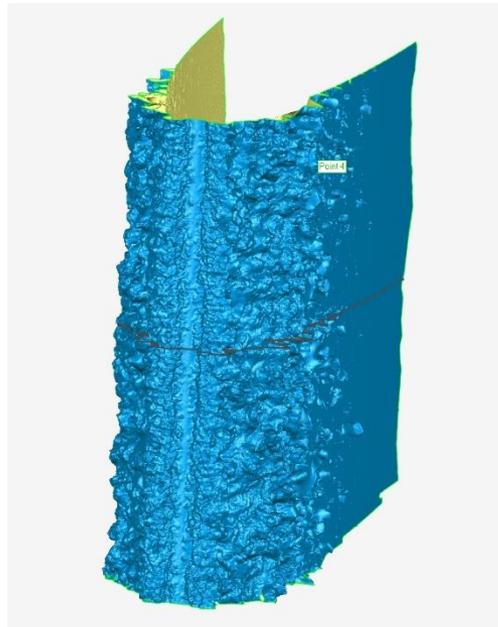
Date/Run	c in	t_{tot} $^{\circ}\text{C}$	V kt	MVD μm	LWC g/m^3	t min	b_0 %	A_c	$b_0 A_c$	n_0	We_L 10^6	We_f 10^{-16}	h_f/d 10^{-9}
12-01-14/03	72	-6.0	99	84	1.2	23.2	82.9	1.61	1.33	0.20	2.30	2.68	0.80
01-19-16/06	21	-2.7	184	31	1.0	4.4	83.2	1.62	1.35	0.21	2.33	2.33	1.42
01-19-16/01	21	-0.2	225	28	0.54	6.3	83.2	1.66	1.38	0.20	3.55	2.81	0.83

3-D Scanned Ice Shapes

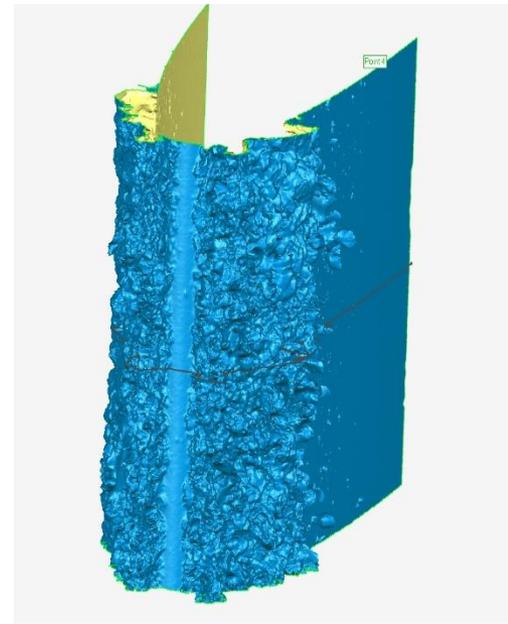
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01-19-16/06



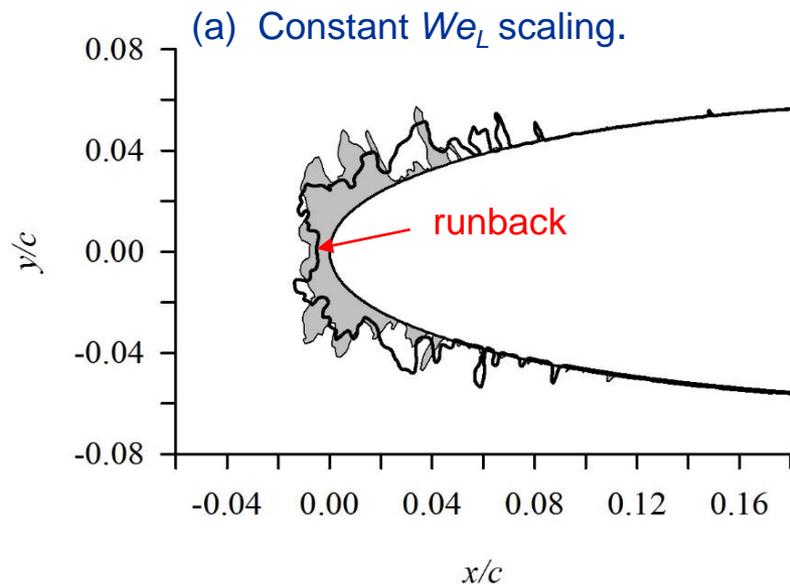
01-19-16/01



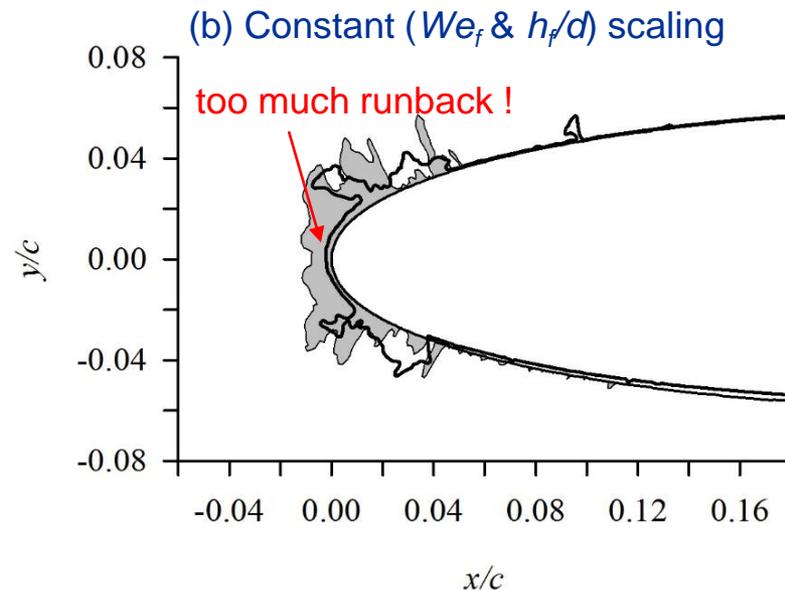
Date/Run	c in	t_{tot} °C	V kt	MVD μm	LWC g/m^3	t min	b_0 %	A_c	$b_0 A_c$	n_0	We_L 10^6	We_f 10^{-16}	$h_f/d,$ 10^{-9}
12-01-14/03	72	-6.0	99	84	1.2	23.2	82.9	1.61	1.33	0.20	2.30	2.68	0.80
01-19-16/06	21	-2.7	184	31	1.0	4.4	83.2	1.62	1.35	0.21	2.33	2.33	1.42
01-19-16/01	21	-0.2	225	28	0.54	6.3	83.2	1.66	1.38	0.20	3.55	2.81	0.83

Ice Shapes Comparison (2)

$$V_R=130kt, MVD_R=85\mu m, n_0=0.2$$



— c = 72 in, 12-01-14/02
— c = 21 in, 01-20-16/01

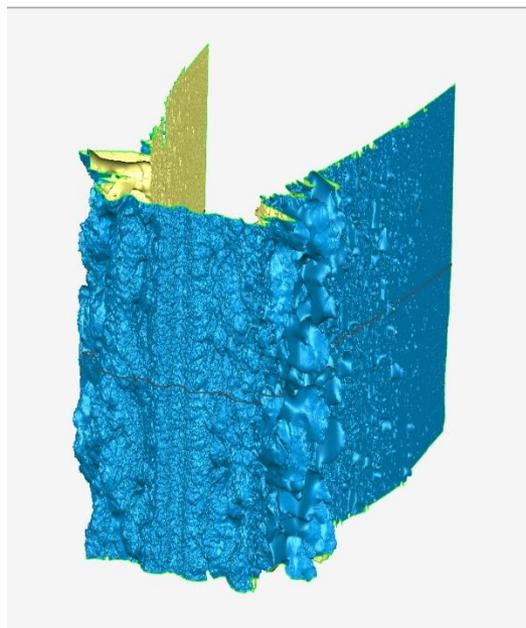


— c = 72 in, 12-01-14/02
— c = 21 in, 01-26-16/01

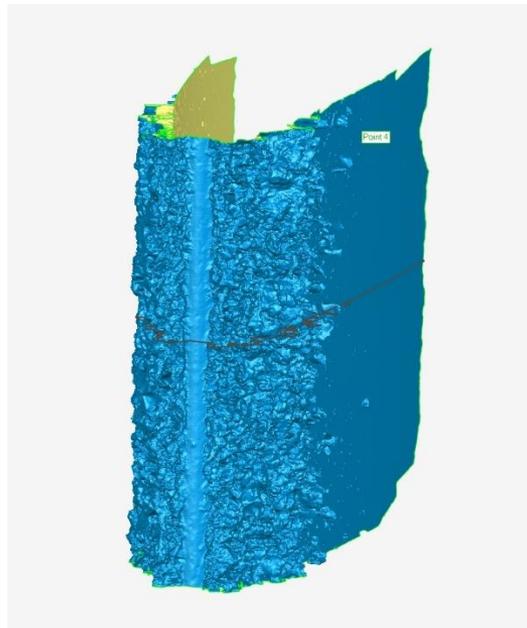
Date/Run	c in	t_{tot} °C	V kt	MVD μm	LWC g/m^3	t min	b_0 %	A_c	$b_0 A_c$	n_0	We_L 10^6	We_f 10^{-16}	h_f/d 10^{-9}
12-01-14/02	72	-5.3	129	85	0.95	22.1	84.7	1.57	1.33	0.21	3.91	1.52	0.51
01-20-16/01	21	-0.4	239	30	0.60	5.5	84.8	1.59	1.34	0.20	3.93	3.06	0.81
01-26-16/01	21	1.7	296	28	0.42	6.7	84.9	1.67	1.41	0.20	6.00	1.71	0.55

3-D Scanned Ice Shapes

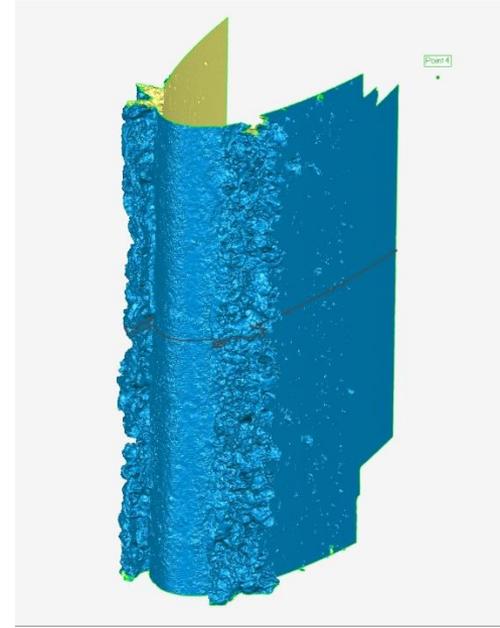
12-01-14/02



01-20-16/01



01-26-16/01

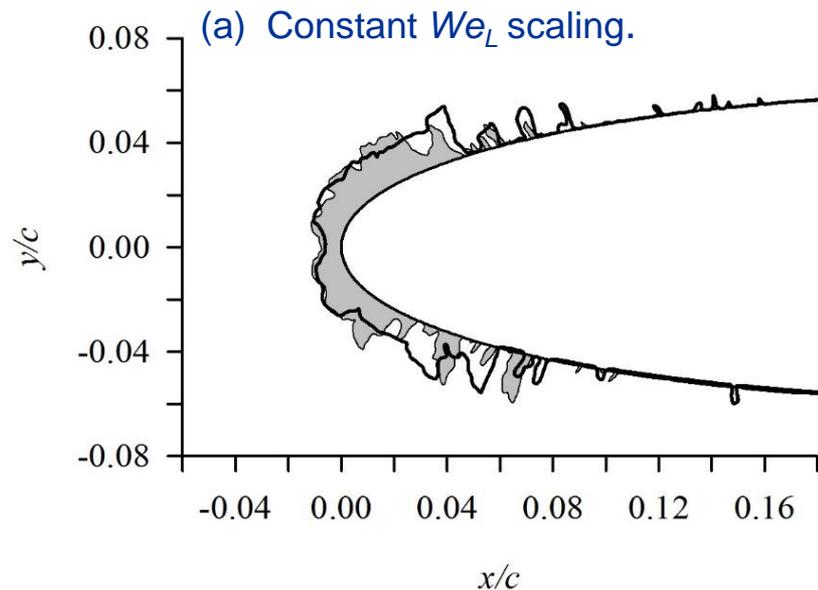


Date/Run	c in	t_{tot} °C	V kt	MVD μm	LWC g/m^3	t min	b_0 %	A_c	$b_0 A_c$	n_0	We_L 10^6	We_f 10^{-16}	h_f/d 10^{-9}
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01-26-16/01	21	1.7	296	28	0.42	6.7	84.9	1.67	1.41	0.20	6.00	1.71	0.55

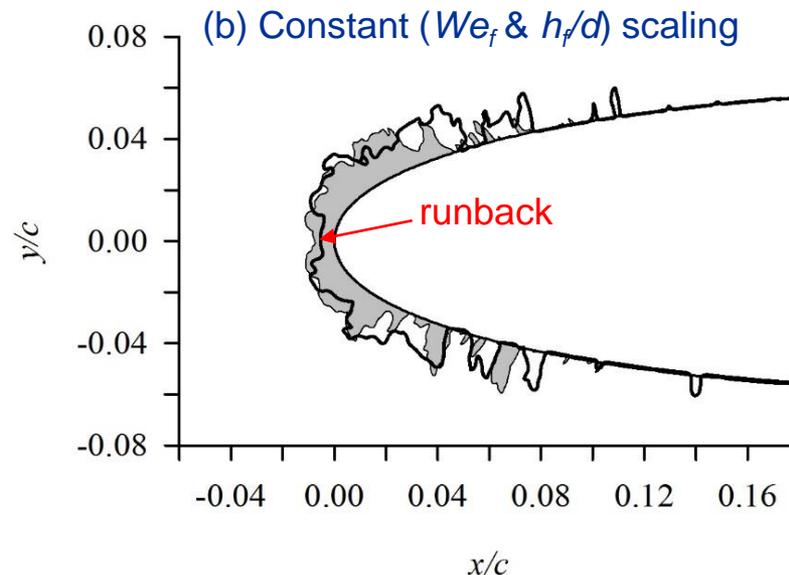


Ice Shapes Comparison (3)

$$V_R=100kt, MVD_R=170\mu m, n_0=0.2$$



— $c = 72$ in, 12-02-14/04
 — $c = 21$ in, 01-20-16/02

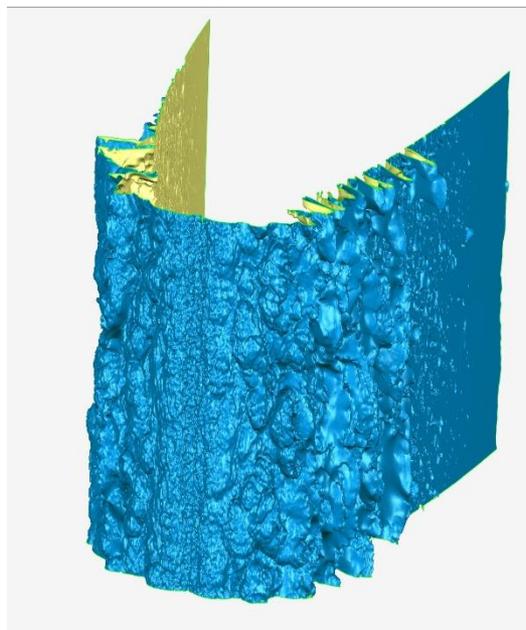


— $c = 72$ in, 12-02-14/04
 — $c = 21$ in, 01-19-16/03

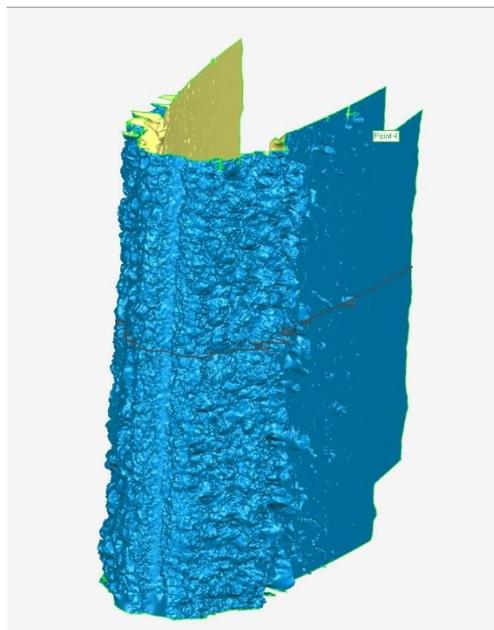
Date/Run	c in	t_{tot} $^{\circ}C$	V kt	MVD μm	LWC g/m^3	t min	b_0 %	A_c	$b_0 A_c$	n_0	We_L 10^6	We_f 10^{-16}	h_f/d 10^{-9}
12-02-14/04	72	-6.9	99	171	1.35	18.6	92.3	1.45	1.34	0.20	2.30	1.10	0.60
01-20-16/02	21	-1.2	185	59	0.50	7.9	92.2	1.46	1.35	0.21	2.34	1.02	0.72
01-19-16/03	21	-0.8	226	58	0.56	5.7	92.6	1.44	1.33	0.20	3.52	1.08	0.60

3-D Scanned Ice Shapes

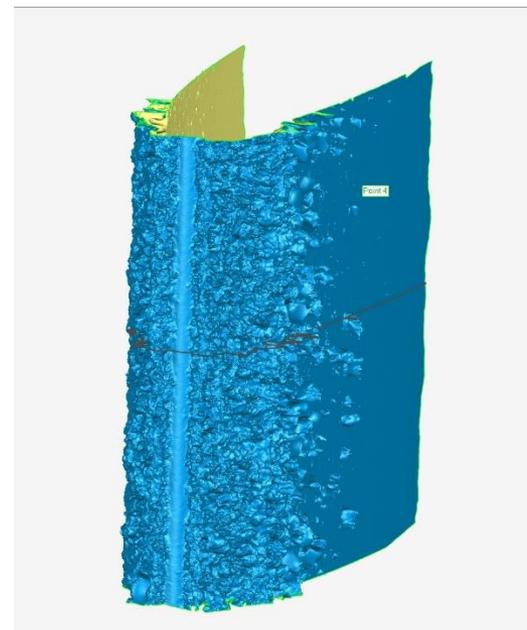
12-02-14/04



01-20-16/02



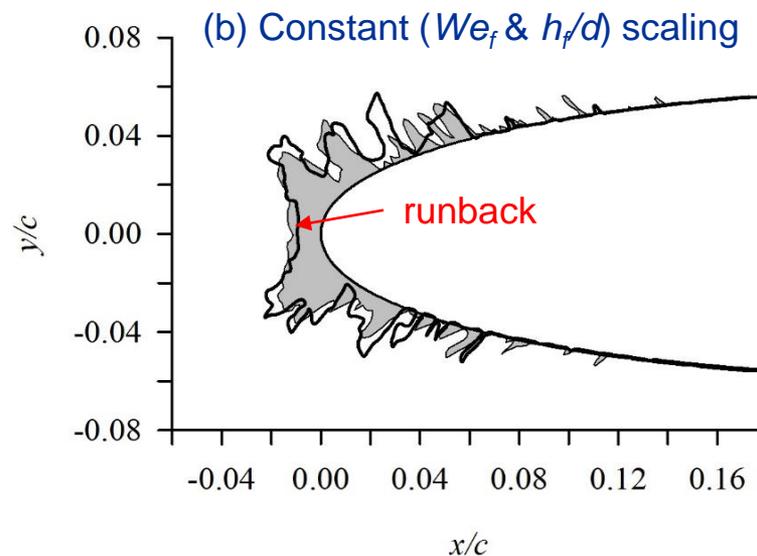
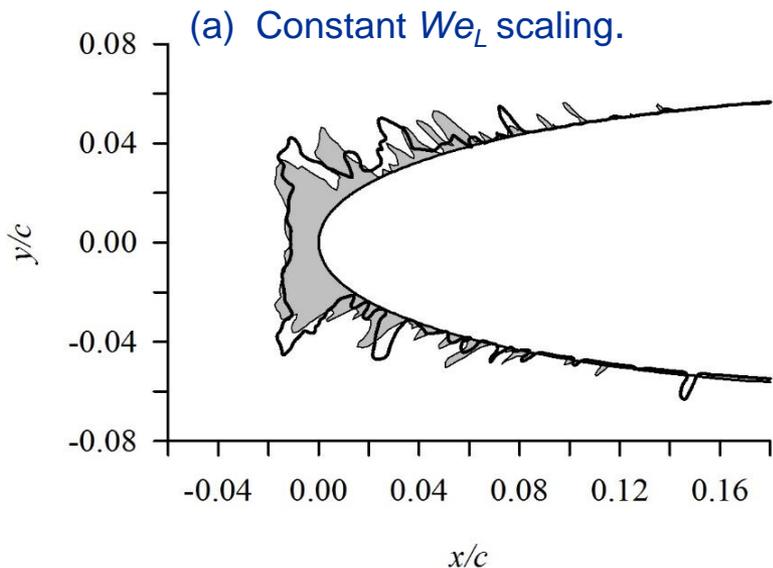
01-19-16/03



Date/Run	c in	t_{tot} °C	V kt	MVD μm	LWC g/m^3	t min	b_0 %	A_c	$b_0 A_c$	n_0	We_L 10^6	We_f 10^{-16}	h_f/d 10^{-9}
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01-20-16/02	21	-1.2	185	59	0.50	7.9	92.2	1.46	1.35	0.21	2.34	1.02	0.72
01-19-16/03	21	-0.8	226	58	0.56	5.7	92.6	1.44	1.33	0.20	3.52	1.08	0.60

Ice Shapes Comparison (4)

$$V_R=100\text{kt}, MVD_R=170\mu\text{m}, n_0=0.3$$



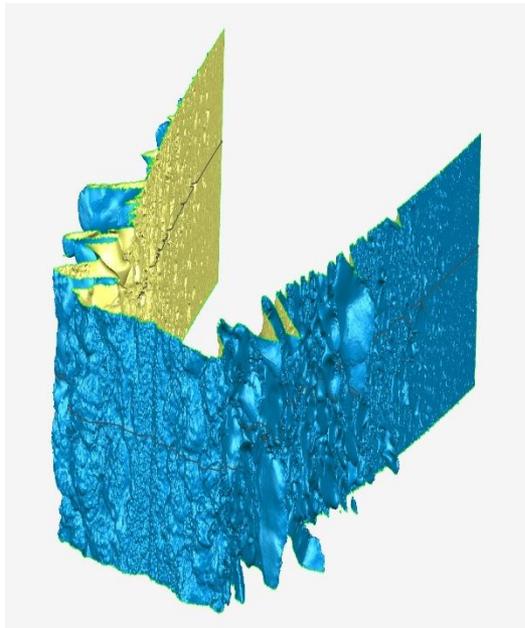
— c = 72 in, 10-20-14/02
— c = 21 in, 01-16-15/03

— c = 72 in, 10-20-14/02
— c = 21 in, 01-27-16/01

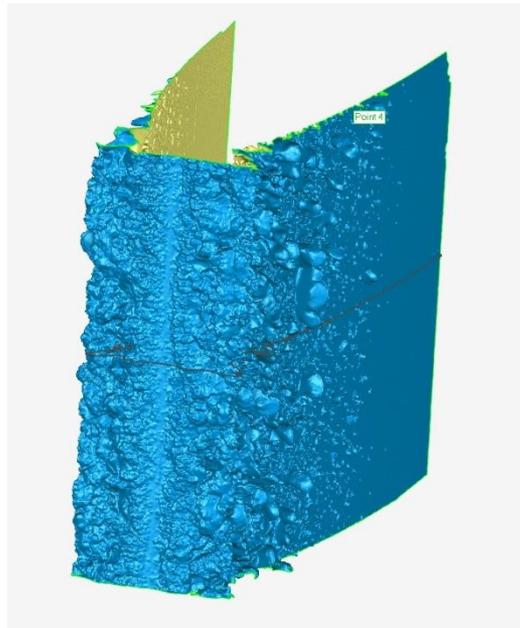
Date/Run	c in	t_{tot} °C	V kt	MVD μm	LWC g/m^3	t min	b_0 %	A_c	$b_0 A_c$	n_0	We_L 10^6	We_f 10^{-16}	h_f/d 10^{-9}
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01-16-15/03	21	-3.1	185	59	0.50	7.3	92.2	1.35	1.25	0.33	2.35	1.01	0.72
01-27-16/01	21	-2.8	226	58	0.56	5.7	92.6	1.44	1.33	0.30	3.50	1.08	0.60

3-D Scanned Ice Shapes

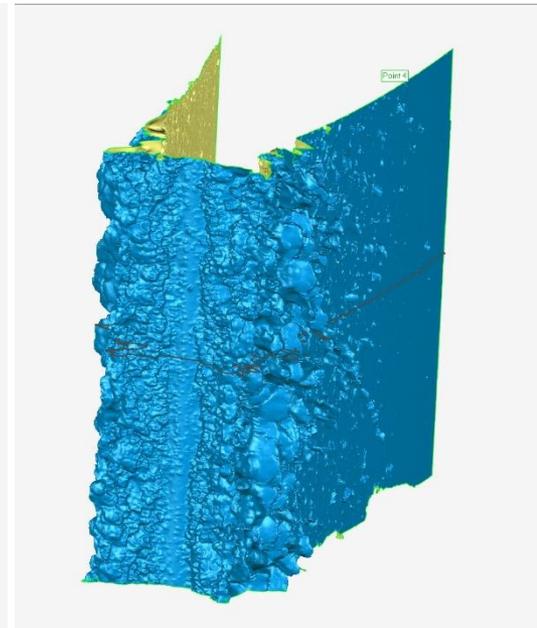
10-20-14/02



01-16-15/03



01-27-16/01



Date/Run	c in	t_{tot} °C	V kt	MVD μm	LWC g/m^3	t min	b_0 %	A_c	$b_0 A_c$	n_0	We_L 10^6	We_f 10^{-16}	h_f/d 10^{-9}
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01-27-16/01	21	-2.8	226	58	0.56	5.7	92.6	1.44	1.33	0.30	3.50	1.08	0.60



Conclusion

- Modified Ruff method evaluated
- Feo method evaluated
- For limited testing at $n_0 = 0.2, 0.3$ (strong glaze icing),
 - Better match of reference ice shapes with constant We_L provided $t_{tot} < -2$ °C.
 - All still within the ice shape repeatability.
- Size of ice accretion, icing limits well simulated.
- Large feather simulations need improvement



Acknowledgement

- Personal thanks to
 - Mr. Quentin Schwinn for the imaging & scan data process support.
 - IRT cloud cal team and the crew for their excellent support.